Development of a sand compaction pile installation tool for the geotechnical drum centrifuge

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ABSTRACT

Sand compaction piles are used in practice for ground improvement of weak subsoil. These columnar inclusions improve the consolidation behaviour as well as reduce the compressibility of the soft ground. The current design procedure of these sand piles is based on simple empirical calculations, which do not take account fully of the sand pile behaviour.

In order to gain a deeper understanding of the behaviour of sand compaction piles, physical investigations are being conducted at ETH in Zurich. The basic system behaviour of soft soil and column is simulated physically by centrifuge modelling. Therefore a sand compaction pile installation tool was developed and applied successfully in an initial test series. This allowed the stress paths encountered by the soil during the construction process of a displacement sand pile to be modelled realistically, because the stress situation in the soil changes significantly due to installation. The results of these first tests are presented in this paper.

1. INTRODUCTION

1.1. Introduction to centrifuge modelling

Geotechnical centrifuges benefit from the additional centripetal forces acting on a model while the centrifuge is rotating. An artificial gravitational field is produced due to the rotation, and is dependent on angular velocity, ω and radius, r (see Fig. 1), [9].

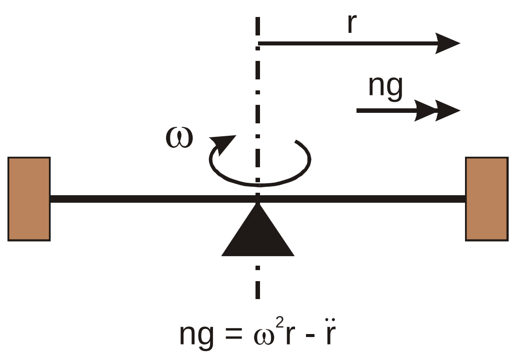


Fig. 1: Principle of centrifuge modelling, $g = 9.81\ m/s^2$, [9].

The mathematical formulation in Fig. 1 includes the component of increased gravity due to radial acceleration. In general, for static cases $\ddot{r}=0$ as the radius does not change during the centrifuge test. Comparing the stresses in different types of physical models (see Fig. 2), the 1/n scale centrifuge model can reproduce the stress distribution of a prototype, which is a factor of n times gravity in size. For example, a soil model of 10 cm height, subjected to 100 times gravity represents the stresses of a soil prototype of 10 m height. The correct modelling of the stresses is the advantage of centrifuge modelling in comparison to small scale physical modelling.

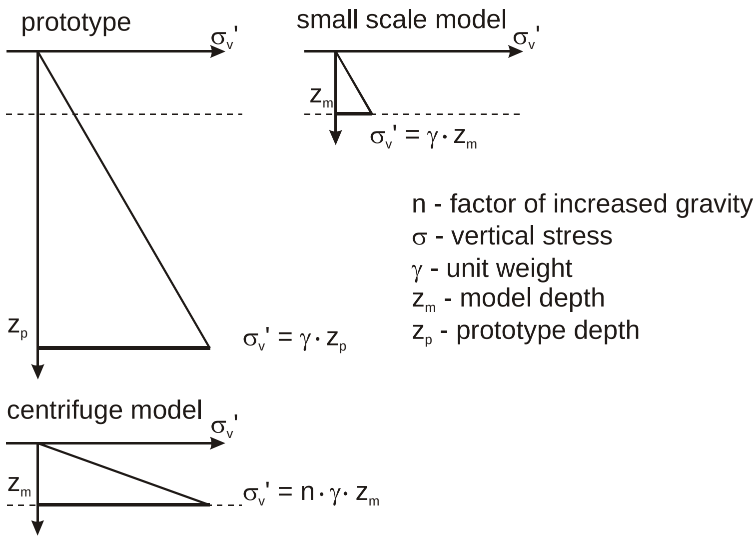


Fig. 2: Comparison of stress distribution in different types of physical models, [2].

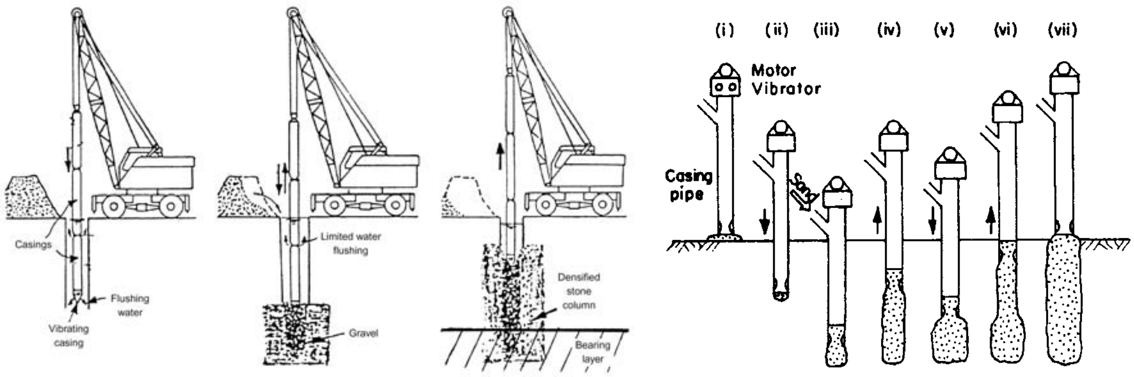
1.2. Methods of sand compaction pile installation

Sand compaction piles are widely used in practice in order to improve soft ground, such as soft clay or peat. In particular, when less settlement-sensitive structures such as embankments are designed, the more cost effective method of sand piles is often preferred, in comparison to creating a piled embankment with reinforced concrete piles.

In general, the methods of sand compaction pile installation can be distinguished into two major groups of displacement and replacement methods. Wet or dry processes are used to insert the columns into the ground. Two kinds of compaction methods of sand piles are common, using vibrating probes or rammed systems, [6], [11], [12].

Fig. 3 shows two of the most frequently used installation methods, the vibroflotation method and the compozer method. The vibroflotation method uses water in order to flush the probe into the ground and soil is removed out of the ground partially and replaced by sand. The compozer method uses compressed air to flush the probe into the ground and the pile is

inserted by displacing the soil. There are several different types of compozer probes, including one with the vibrator at the top and one at the base of the probe.



(a) (b)

Fig. 3: Construction of stone columns: (a) vibroflotation (wet process), (b) vibro-compozer (dry process), [1], [6].

The design procedure for sand compaction piles is based on empirical and analytical approaches. The most commonly used method in German speaking regions is after Priebe, [7], [8]. Some key assumptions such as the even settlements of the soil body and the pile grid, do not apply to embankment loads. Also, the change in stress state due to the construction process of the sand piles is not taken into account. The method after Priebe, [7], [8], gives an improvement factor referring to the unimproved ground. The calculation is fairly robust and usually gives a conservative value.

In order to overcome these deficiencies and to gain a better understanding of the behaviour of sand compaction piles, physical investigations are being carried out by means of the geotechnical centrifuge. As a first step, an installation tool for sand pile construction was developed. The first experiences gained with this tool are presented herein.

2. SAND COMPACTION PILE INSTALLATION IN THE DRUM CENTRIFUGE

The centrifuge laboratory at ETH Zurich uses a geotechnical drum centrifuge with a diameter of 2.2 m. The centrifuge is able to run tests a maximum g-level of 440 times gravity acting in a horizontal plane. A section through the centrifuge construction is shown in Fig. 4.

The soil model will be installed in the drum channel. All tools are mounted on the tool table. The channel and the tool table can be controlled independently. This allows the tool table to be stopped and to be accessed while the drum channel is continuously rotating when the

safety shield is lowered during a test. This is an advantage of the drum centrifuge and it will be made use of in this series of tests.

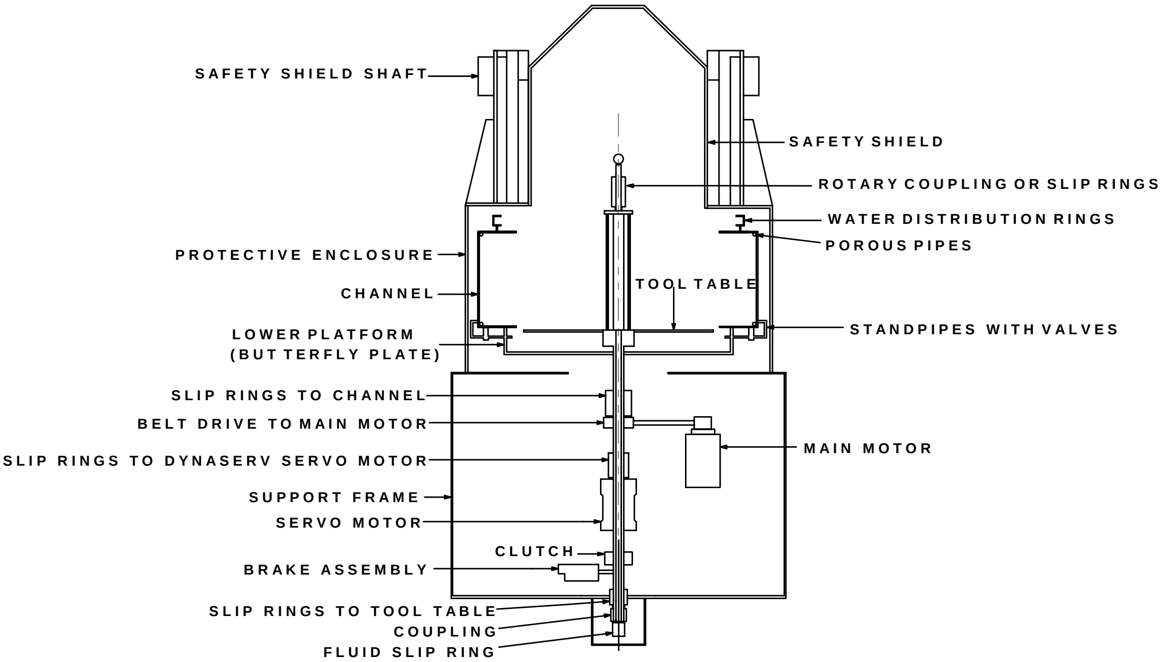


Fig. 4: Sketch of the ETHZ Drum Centrifuge, [10].

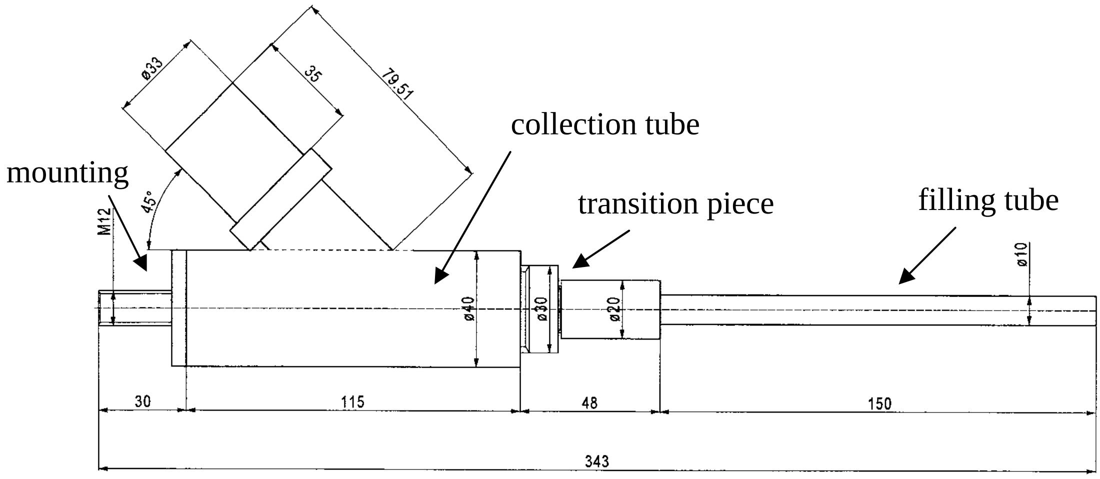
For further information, Springman et al. [10] give a detailed technical description of the geotechnical drum centrifuge at ETH Zurich.

2.1. Installation tool

In order to model the sand compaction pile installation process, an installation tool has been developed for the geotechnical drum centrifuge. This installation tool reproduces the production process of a displacement pile using a dry construction method similar to the compozer method (Fig. 3b).

Other previously used methods of sand pile installation were conducted under 1 g, for instance the sand piles were frozen and pressed into holes augered in the clay or simply sand was poured into predrilled holes. These methods are not able to model the stress situation that occurs during the installation process. Only piles installed ‘in flight’ are able to represent the stress situation of the prototype pile in the centrifuge, [3], [4].

The new tool (Fig. 5) consists of mainly 4 parts: mounting, collection tube, transition piece and filling tube. All the parts are made of aluminium except the filling tube, which is made of stainless steel.



(a)

(b)

Fig. 5: Sand compaction pile installation tool: a) technical drawing, dimensions [mm], b) mounted on the tool table.

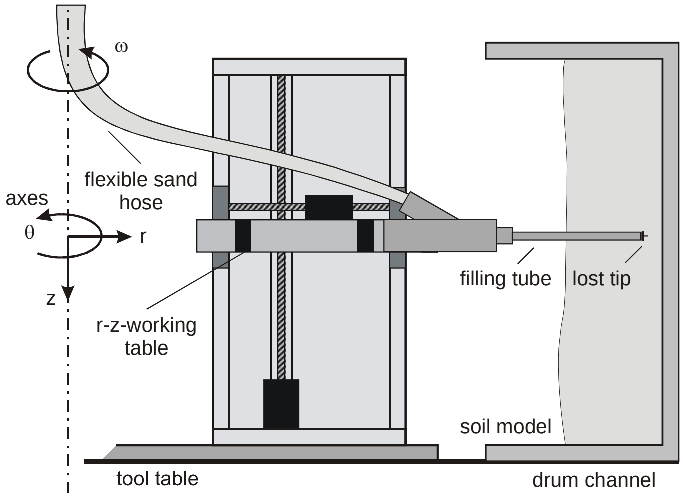
A flexible hose is mounted on the inlet for the supply of sand for pile installation. In the transition piece, the aperture reduces to a diameter of 7.5 mm, while the filling tube has an inner diameter of 8.4 mm. Like an hourglass, and with aid of enhanced gravity, the sand is dropping through the small opening of the transition piece without getting blocked while the centrifuge is rotating.

2.2. Installation procedure

The installation procedure is drawn schematically in Fig. 6a. The sand compaction pile installation tool is mounted in the r-z axes on the working table of the tool table, Fig. 6b.

In order to prevent plugging of the filling tube by clay, a lost tip system is being applied. A drawing pin is simply stuck into the surface of the clay model. When the filling tube is driven into the clay, the cap of the drawing pin closes the opening of the filling tube. When reaching

the desired depth, sand is filled into the inlet sand hose. Slowly the installation tool is drawn out and the sand will flow out of the filling tube. The drawing pin remains in the soil model.



(a)

(b)

Fig. 6: Sand compaction pile installation tool in the drum centrifuge: a) schematical drawing, b) mounted at the tool table.

Compaction of the sand pile is achieved by slowly drawing out and re-inserting the installation tool again into the soil. Depending on the relationship between the degree of withdrawal and insertion, different sizes and densities of the sand pile can be obtained.

In order to produce a grid of sand compaction piles, the dimensions of the grid must be marked with drawing pins on the surface of the clay model in the z-θ axes before beginning of the test. An accuracy of about 0.5 mm is necessary in both z and θ direction. Otherwise the filling tube misses the pin when being inserted, as the tube gets blocked with clay and the pile cannot be produced properly. The control system of the drum centrifuge allows an accuracy of about 0.02° in θ direction which represents 0.2 mm at the clay surface. The accuracy in z direction is about 0.05 mm.

3. CENTRIFUGE TESTING

For centrifuge testing, reconstituted clay from Birmensdorf and crushed quartz sand from Benken with a sieved fraction of 0.5 - 1.0 mm were used. Both materials come from the region of Zurich.

The clay is classified as CM with liquid limit of 42.4 % and plasticity index of 25.7 %, [5].

3.1. Model preparation

The clay model was prepared in the common way, see Fig. 7. Firstly the clay was mixed with water to a water content of about 82 % (Fig. 7a). Then the air was removed in the vacuum chamber until the material was fully saturated (Fig. 7b).

The clay was consolidated using a consolidation press in a 40 cm diameter container (Fig. 7c). Six load steps were applied with vertical stresses of 6, 12, 25, 50 and 100 kPa. Drainage was allowed to both sides of the clay model and each load step took about one week time.

The container consists of 2 parts. The top part is needed because the filling height of the clay exceeds by far the height of the container which was later used as strong box in the centrifuge. The strong box has a height of 20 cm. Consolidation occurred from the original height of 285 mm and a water content of 82 % to a height of 140 mm and a water content of 37 %.

(a) (b) (c)

Fig. 7: Preparation of reconstituted clay model: a) clay mixing, b) vacuum chamber, c) consolidation.

3.2. Test series

The results of the test series conducted at a level of 50 g are discussed here. Several alterations of the technical equipment were necessary before the sand compaction pile installer worked properly. In particular, the length of the hose has to be determined accurately for smooth flow of sand into the collection tube. The sand flow caused problems repeatedly during the tests. Only a certain grid of sand piles can be produced using one hose. For bigger grids, several hoses of different lengths are needed and they have to be changed while the drum channel of the centrifuge is running.

The grid of sand compaction piles, which were installed, is shown in Fig. 8. Problems occurred during the installation of pile no. 2, 3, 9 and 10 due to insufficient sand flow and were not produced properly.

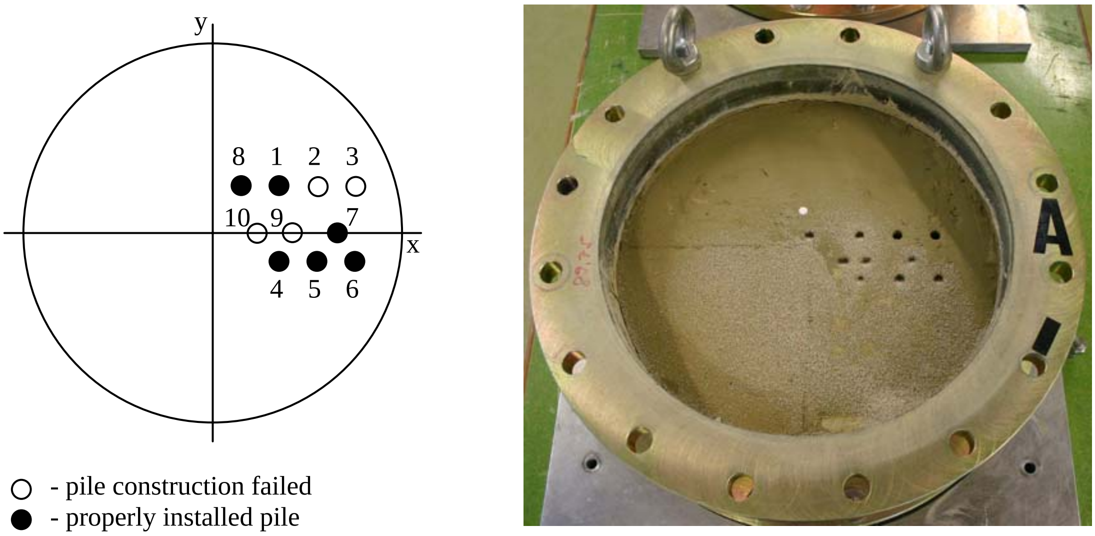
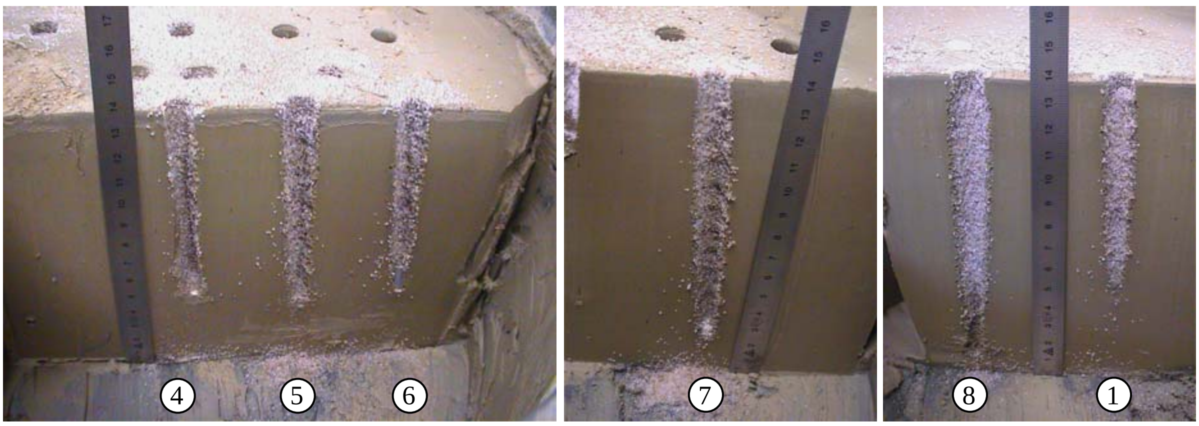


Fig. 8: Grid of installed sand compaction piles.

Different degrees of compaction were tried out by various withdrawal and re-insertion distances. Pile 8 is compacted by a ratio of 15/10, which means 15 mm withdrawal to 10 mm re-insertion. This pile has a maximum diameter of 15 mm (Fig. 9c).

Pile 7 in Fig. 9b was compacted by the ratio of 20/10 and achieved a diameter of about 11 mm. Pile 5 in Fig. 9a was compacted by a ratio of 14/7 and also achieved a diameter of 11 mm. Pile 6 in Fig. 9a was compacted by the same quotient of 2 as pile 7 and 5 but with a ratio of 8/4. This pile had a diameter of about 10 mm. Because of the bigger strokes pile 7 showed a more caterpillar-shape than pile 6.



(a) (b) (c)

Fig. 9: In flight inserted sand piles: a) pile 4, 5 and 6, b) pile 7 and c) pile 8 and 1.

In comparison pile 4 in Fig. 9a was not compacted. This pile seemed to have a concave shape with a diameter of 9 mm, remembering the outer diameter of the filling tube is 10 mm.
All piles had slightly different lengths because only one sand hose were provided for the tests and the variation of the pile grid had to be compensated by different pile depths.
In the following Tab. 1, an overview is given of the achieved diameters of the piles according to the compaction ratio.

Tab. 1: Degree of compaction.

pile no.	1	4	5	6	7	8
compaction ratio [mm/mm]	8/4	-	14/7	8/4	20/10	15/10
diameter [mm]	11	9	11	10	11	15

The quotient of the compaction ratio has the major influence on the compaction taking the diameter of the pile as reference to the degree of compaction. The same quotient seems to achieve similar diameters. A smaller quotient certainly gives a bigger pile.

4. CONCLUSIONS

The sand compaction pile installation tool is able to reproduce the production process and the stress paths of sand compaction piles in the drum centrifuge close to reality. The system using a drawing pin to simulate a lost tip could successfully be applied in the first test series. It is possible to produce a sand pile grid without stopping the centrifuge.
The compaction of the sand pile can be achieved by withdrawing and re-inserting the installation tool. This ratio has a decisive effect on the size of the pile and the degree of compaction.

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